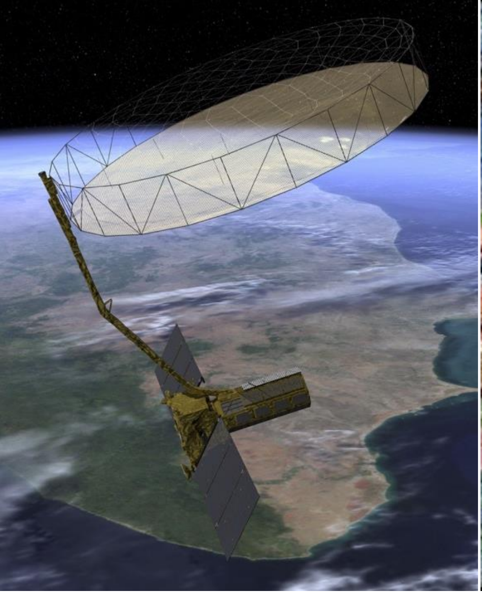
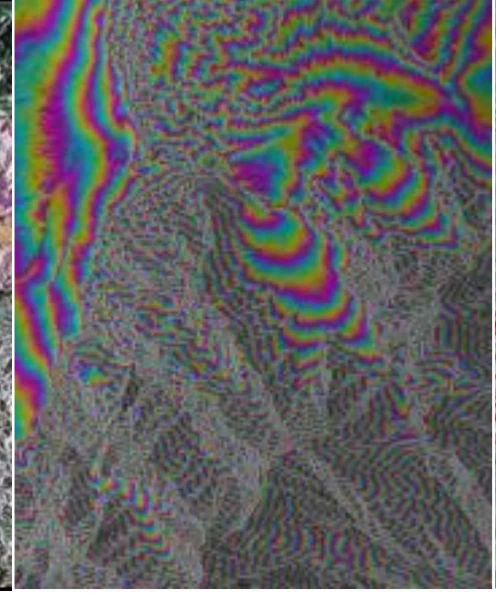





The Phased-Array Reflector Antenna System on the NASA-ISRO SAR Mission Concept

Paul A Rosen, Scott Hensley, Scott Shaffer, Wendy Edelstein, Yunjin Kim, Pam Hoffman, Paolo Focardi, Joe Vacchione
Jet Propulsion Laboratory, California Institute of Technology

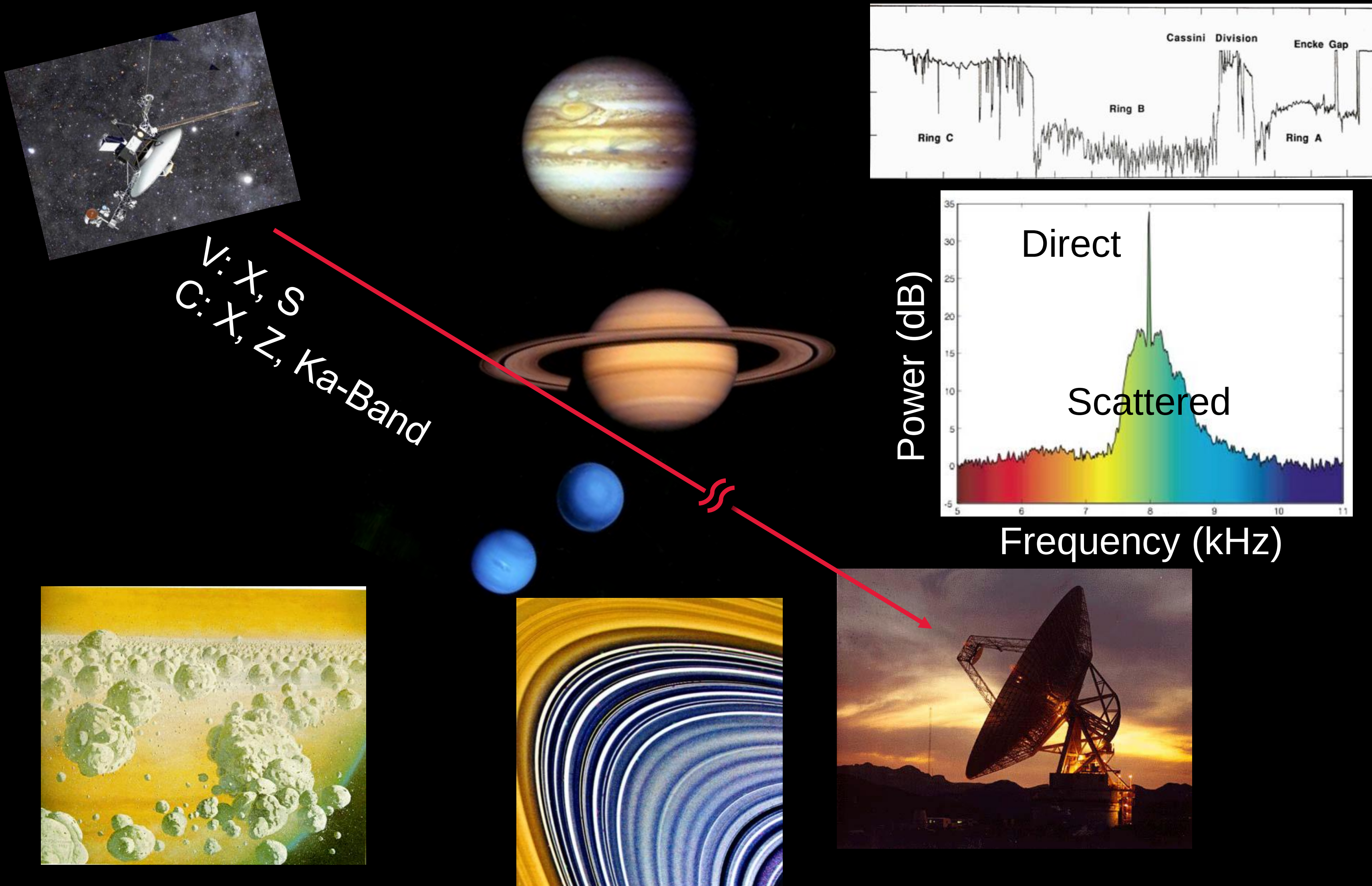
Raj Kumar, Tapan Misra, Rakesh Bhan
ISRO Space Applications Centre

Raju Sagi
ISRO Satellite Centre

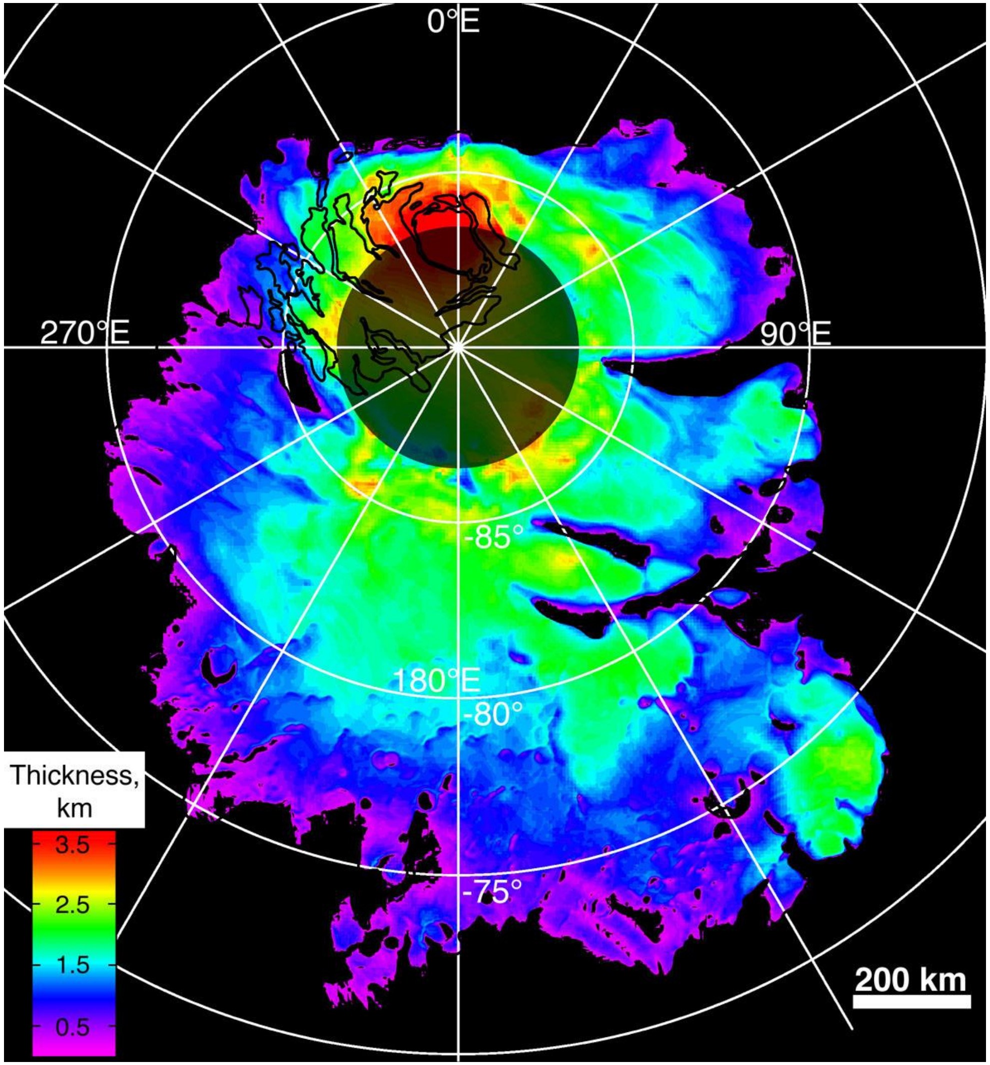
iAIM 2017
Bengalaru, India
November 24, 2017

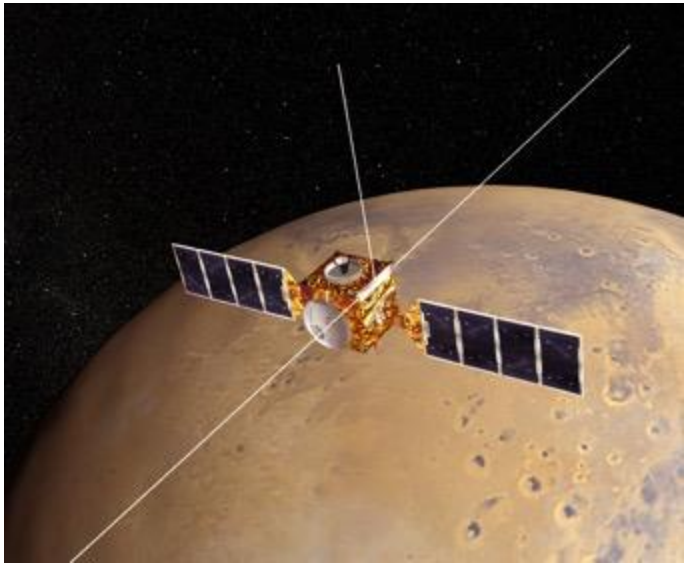
Jet Propulsion Laboratory
California Institute of Technology

Voyager/Cassini Radio Occultation – Bistatic CW Radar Remote Sensing



Mars South Polar Cap Thickness from MARSIS

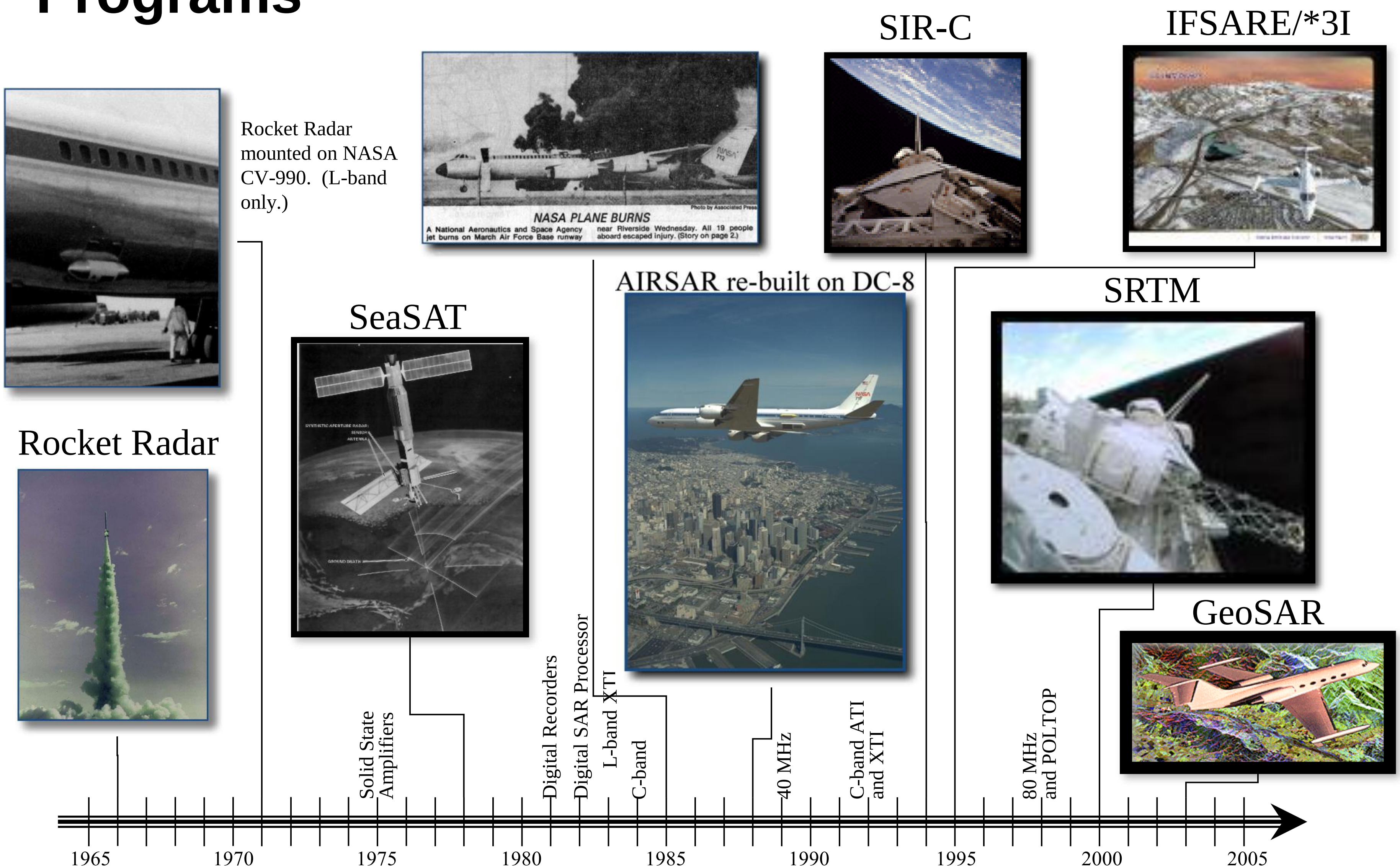




HF with wide relative bandwidth

Probes subsurface and ionosphere

JPL Coupled Airborne and Spaceborne SAR Programs



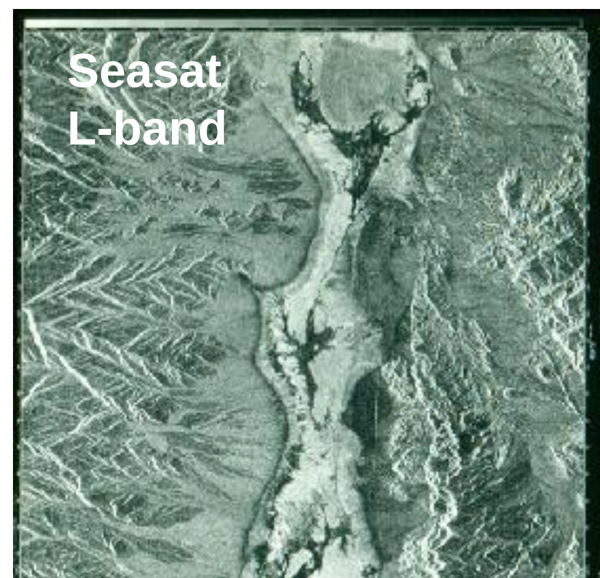
JPL

Outline of talk

- What is SAR?
- What is NISAR?
  - Science
  - Measurements
  - Design drivers
- What is SweepSAR?
- What is the NISAR antenna?
- What are the challenges in building NISAR?
- Where are we in the program?
- Summary

Radar Remote Sensors

- **Altimeters**
  - height of a surface
- **Sounders/Profilers**
  - volume composition and structur
- **Scatterometers**
  - surface composition and roughn
- **Synthetic Aperture Radar (SAR)**
  - surface composition and roughness imagery
- **Polarimeters**
  - improves surface or volume structure information
- **Interferometers**
  - topography and topographic change



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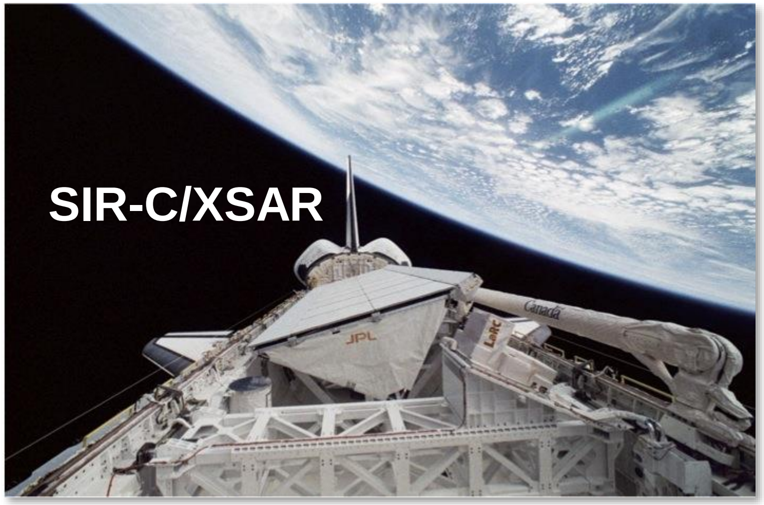

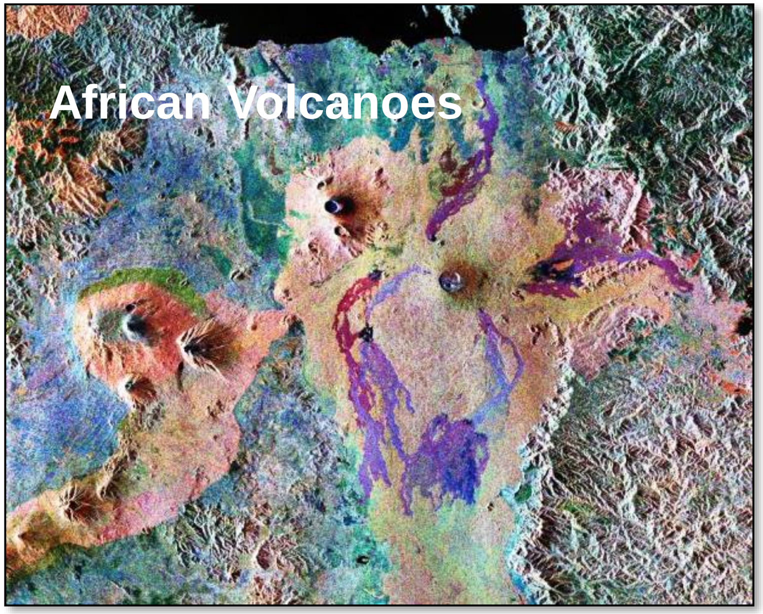

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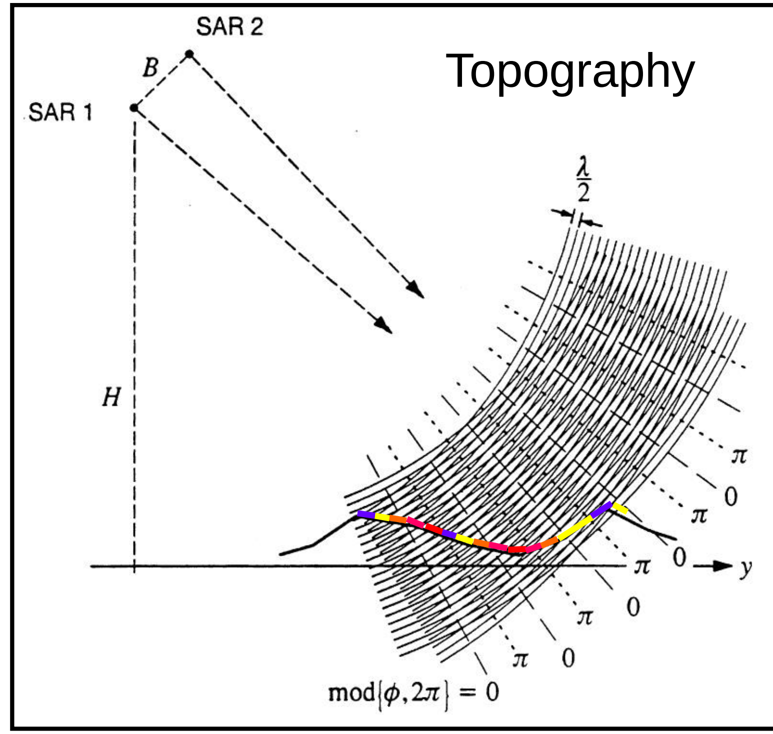
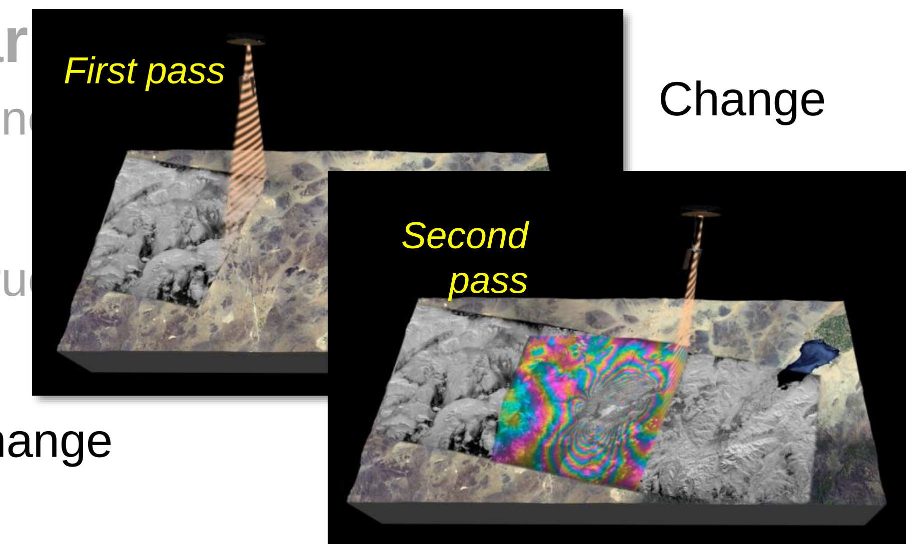




Change

NISAR Mission Objectives Responsive to US National Academy

Key Scientific Objectives:

- Understand the response of ice sheets to climate change and the interaction of sea ice and climate
- Understand the dynamics of carbon storage and uptake in wooded, agricultural, wetland, and permafrost systems
- Determine the likelihood of earthquakes, volcanic eruptions, and landslides

Key Applications Objectives:

- Understand societal impacts of dynamics of groundwater, hydrocarbon, and sequestered CO_2 reservoirs
- Provide agricultural monitoring capability in support of food security objectives
- Apply NISAR's unique data set to explore the potentials for urgent response and hazard mitigation

To be accomplished in partnership with the Indian Space Research Organisation (ISRO) through the joint development and operation of a space-borne, dual-frequency, polarimetric, synthetic aperture radar (SAR) satellite mission with repeat-pass interferometry capability

ISRO Science and Applications Objectives

1. **Ecosystem Structure:** 1.1 Agriculture Biomass & Crop Monitoring; 1.2 Forest Biomass; 1.3 Biomass Change; 1.4 Mangroves / Wetlands; 1.5 Alpine Vegetation; #Vegetation Phenology and Vulnerability; #Vegetation soil moisture; #Ecosystem stress assessment.

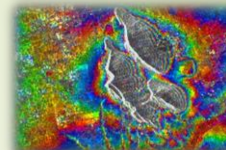
2. **Land Surface Deformation**: 2.1 Inter-seismic / Co-seismic Deformations; 2.2 Landslides; 2.3 Land Subsidence; 2.4 Volcanic Deformations

3. **Cryosphere:** 3.1 Polar Ice Shelf / Ice sheet; 3.2 Sea Ice Dynamics; 3.3 Mountain Snow/ Glacier 3.4 Glacier Dynamics (Himalayan Region); #Glacier hazards; #Climate response to glaciers; #Advisory on safer marine navigation and sea ice.

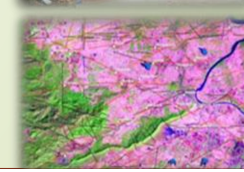
4. **Coastal Studies & Oceanography:** 4.1 Coastal erosion / shoreline change; 4.2 Coastal subsidence and vulnerability to sea-level rise; 4.3 Coastal bathymetry; 4.4 Ocean surface wind; 4.5 Ocean wave spectra; 4.6 Ship detection; #Possible use of SAR for tropical cyclone; #Coastal watch services

5. **Disaster Response:** 5.1 Floods; 5.2 Forest Fire; 5.3 Oil Spill; 5.4 Earthquakes / Others

6. **Geological Applications:** 6.1 Structural & Lithological mapping; 6.2 Lineament mapping; 6.3 Paleo-Channel study; 6.4 Geomorphology; #Land degradation mapping; #Geo-archaeology; #Mineral explorations



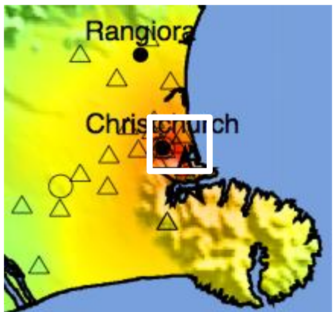


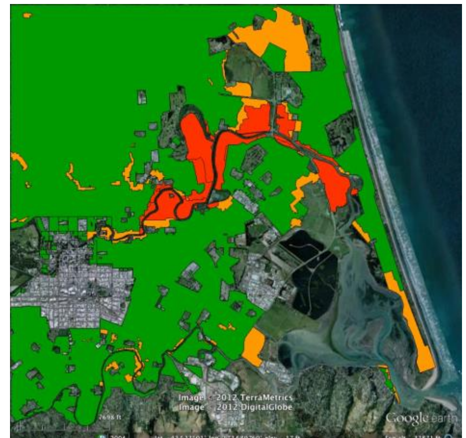
NASA Requirements for NISAR

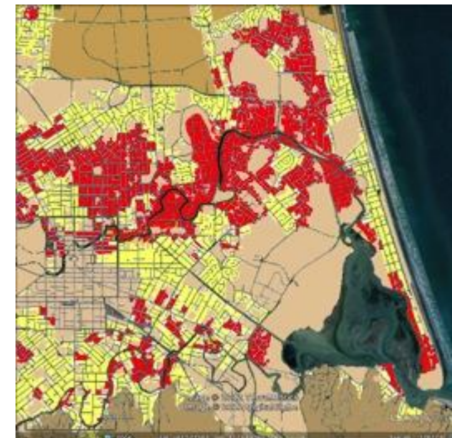
- From US Perspective, NISAR requires
  - Global coverage
  - Dense sampling in time
  - Vector measurements
- In order to accomplish new science
  - Global inventory of earthquakes and volcanos (above sea level)
  - Global inventory of biomass changes over the mission
  - Global inventory of wetlands and cultivated agriculture
  - Global dynamics of ice sheets and sea ice
- And to develop a community of applications users for
  - Disaster response
  - Infrastructure monitoring
  - Agriculture and forestry applications

Application to Improve Disaster Response

Damage Proxy Map from radar data







Shakemap released by USGS NEIC

Radar data acquired by ALOS satellite

Official damage map released based on ground observations

Official damage map updated based on ground observations

2011 | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct

M6.3 Christchurch Earthquake

185 people killed > 1000 buildings destroyed Over US $30 billion damage

Sang-Ho Yun, JPL

Original ALOS Data © JAXA, METI 2011

Official damage map provided by the New Zealand Government (http://data.govt.nz)

JPL

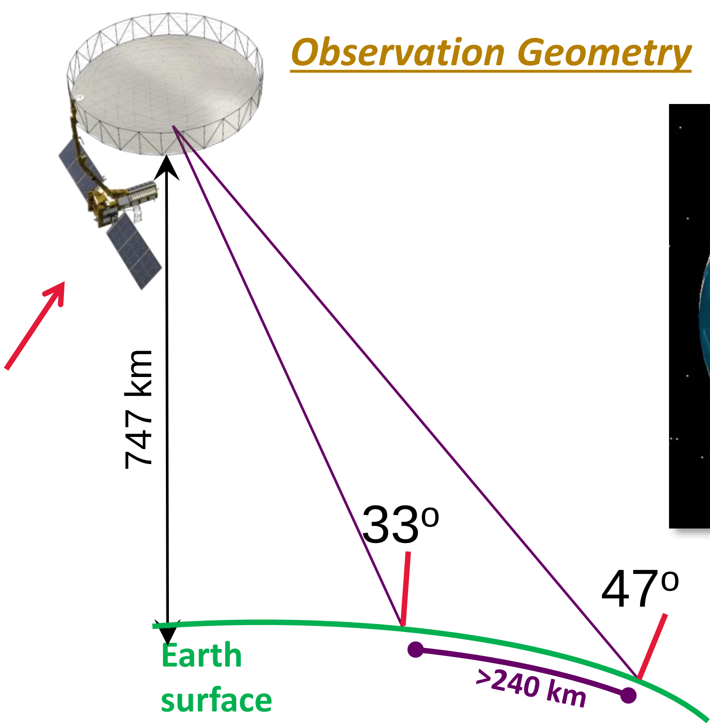
NISAR
NASA-ISRO SAR Mission

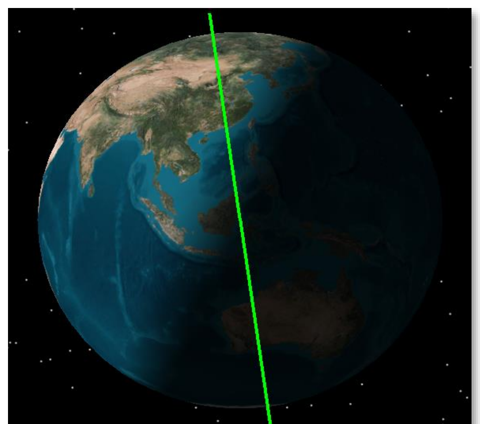
NISAR Characteristic:	Enables:
L-band (24 cm wavelength)	*Low temporal decorrelation and foliage penetration*
S-band (12 cm wavelength)	*Sensitivity to lighter vegetation*
SweepSAR technique with Imaging Swath > 240 km	*Global data collection*
Polarimetry (Single/Dual/Quad)	*Surface characterization and biomass estimation*
12-day exact repeat	*Rapid Sampling*
3 – 10 meters mode-dependent SAR resolution	*Small-scale observations*
Pointing control < 273 arcseconds	*Deformation interferometry*
Orbit control < 500 meters	*Deformation interferometry*
L/S-band > 50/10% observation duty cycle	*Complete land/ice coverage*
Left/Right pointing capability	*Polar coverage, north and south*

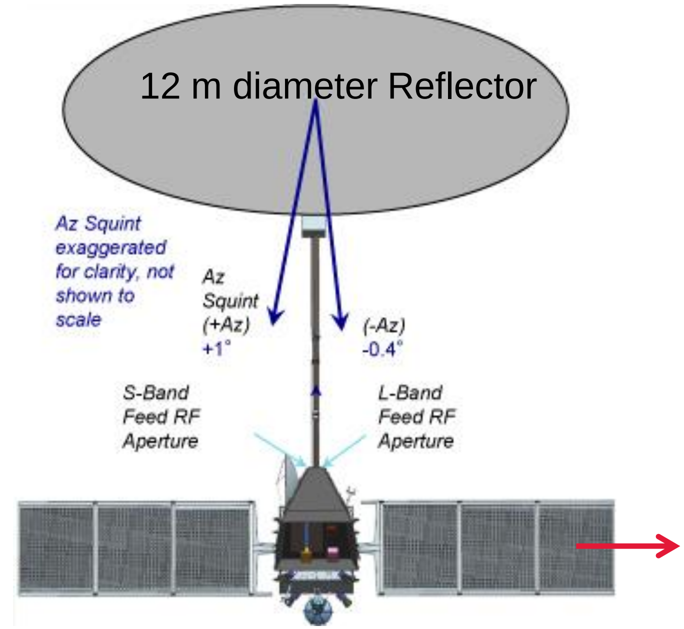
NISAR Imaging and Orbit Geometry

- Wide swath in all modes
- Data acquired ascending and descending
- Left/right pointing capability

Observation Geometry

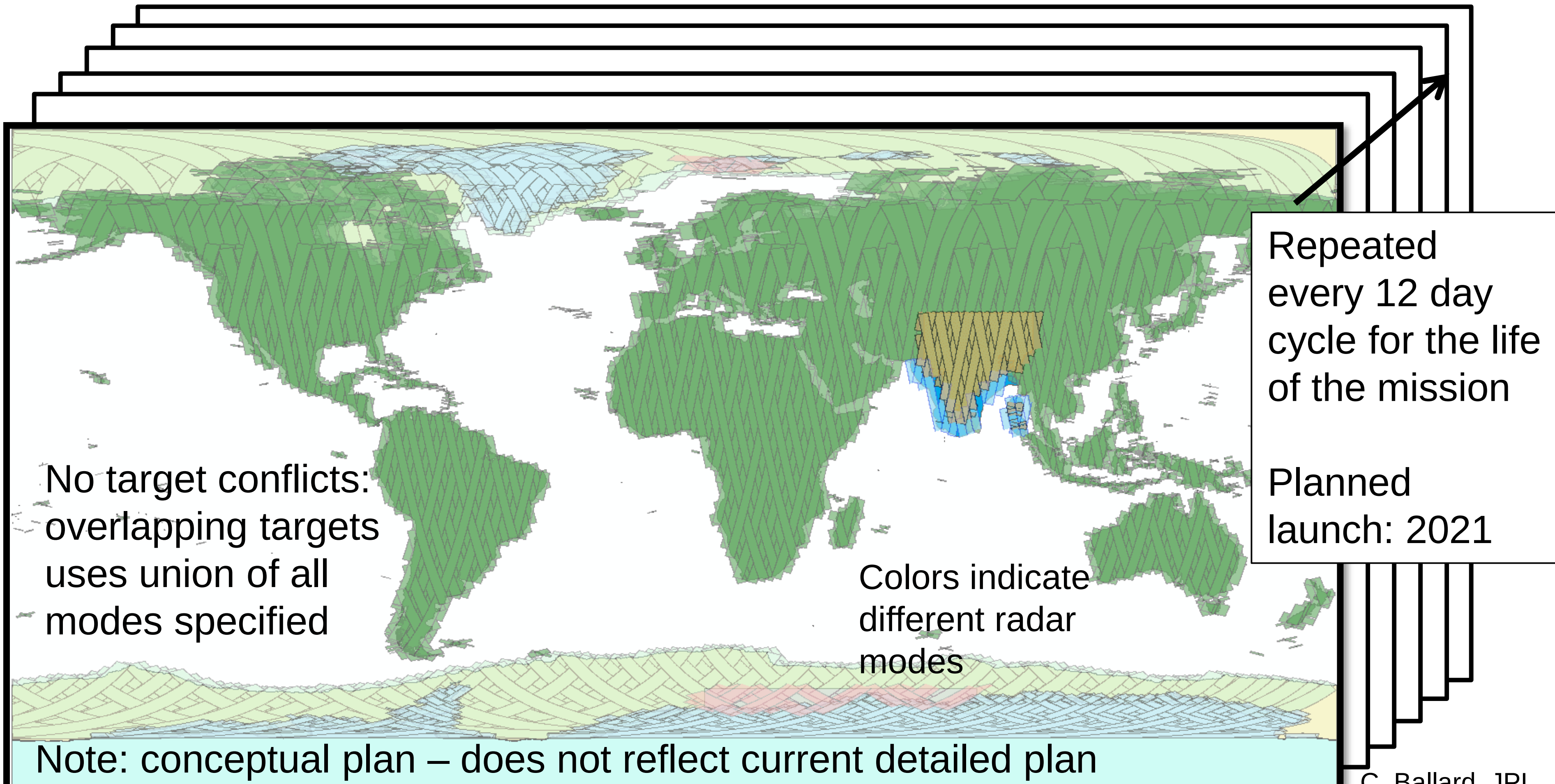






6 AM / 6 PM Orbit
98.5° inclination
Arctic Polar Hole: 87.5R/77.5L
Antarctic Polar Hole: 77.5R/87.5L

NISAR Systematic Observations
L-band globally – S-band regionally

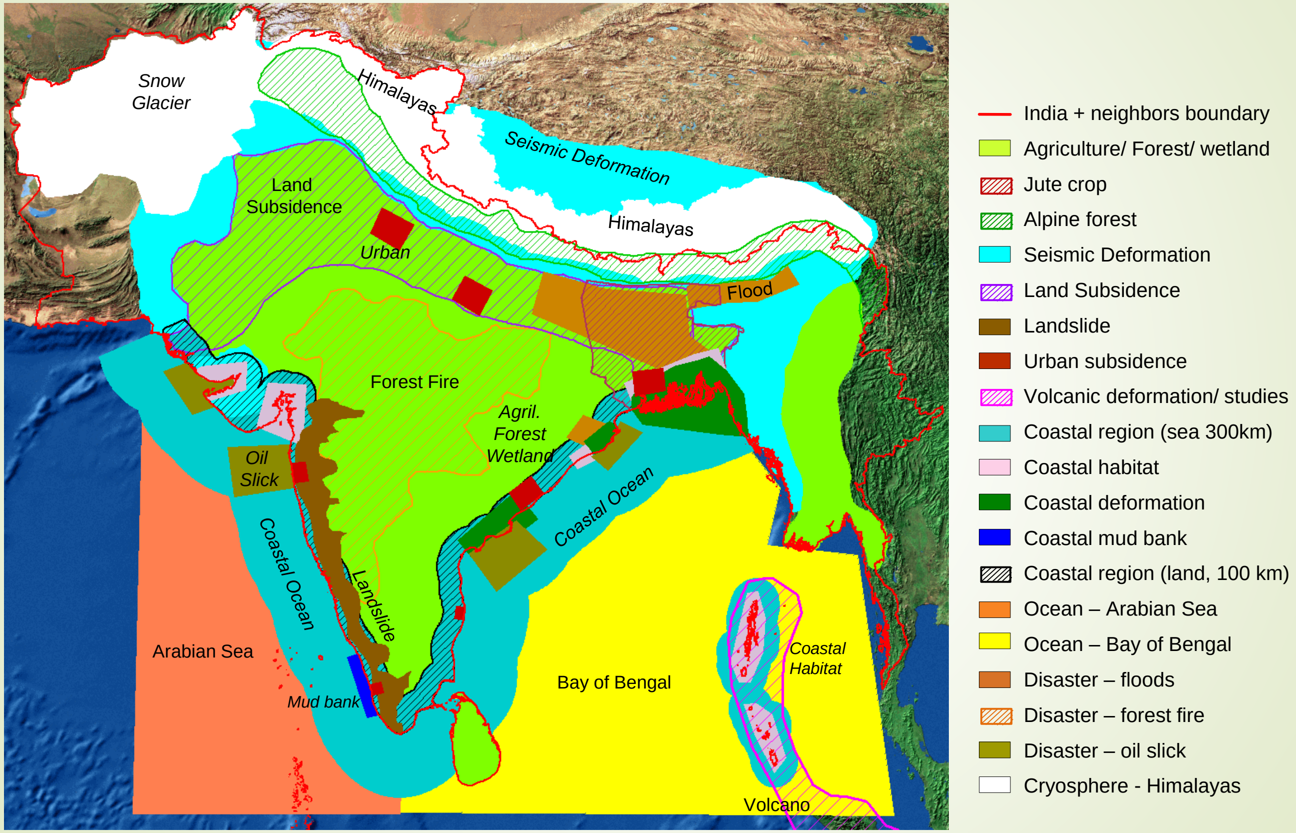


C. Ballard, JPL

Persistent updated measurements of Earth

ISRO Targets over India and Surroundings

These exclude polar targets



NISAR Science Observing/Operations Modes Blanket Land and Ice Coverage Every 12 Days

- Observation strategy employs a subset of possible modes

Observation Strategy	L-band		S-band		Culling Approach	
Science Target	Mode+	Resolution	Mode	Resol.	Sampling	Desc Asc
Background Land	DP HH/HV	12 m x 8 m			cull by lat	
Land Ice	SP HH	3 m x 8 m			cull by lat	
Sea Ice Dynamics	SP VV	48 m x 8 m			s = 1 p	
Urban Areas		6 m x 8 m			s = 1 p	
US Agriculture	QP HH/HV VV/VH				s = 1 p	
Himalayas			CP RH/RV		s = 1 p	
India Agriculture					s = 1 p	
India Coastal Ocean			DP HH/HV or VV/VH		s = 1 p	
Sea Ice Types	DP VV/VH				s = 3 p	

Benefits of both US-contributed L-band SAR and India-contributed S-band SAR

- *Global* L-band and *globally-distributed but targeted* S-band data with unprecedented spatial and temporal sampling will drive new directions in science and applications, including high-resolution soil-moisture and crop assessments

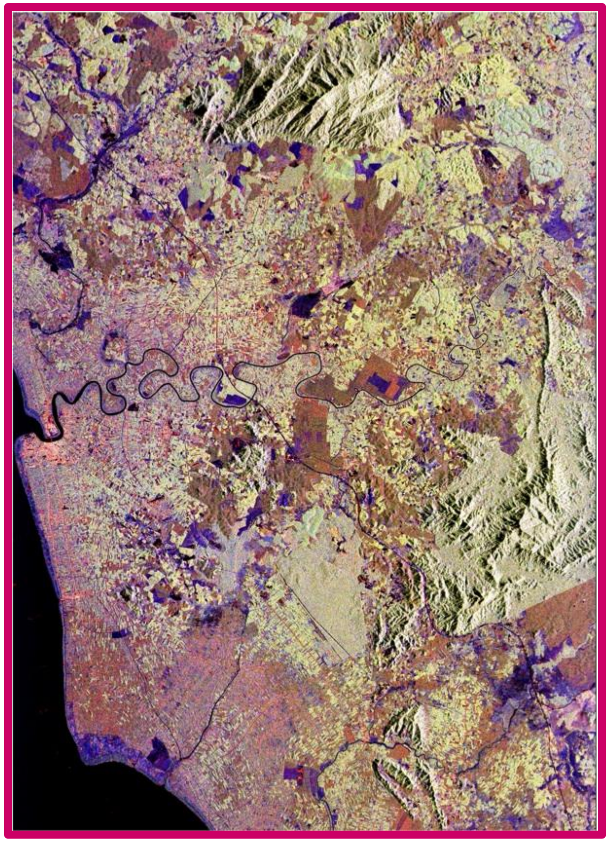
Wheat Fields,

Dnieper River, Ukraine

Red: LHH
Green: LHV
Blue: CHV

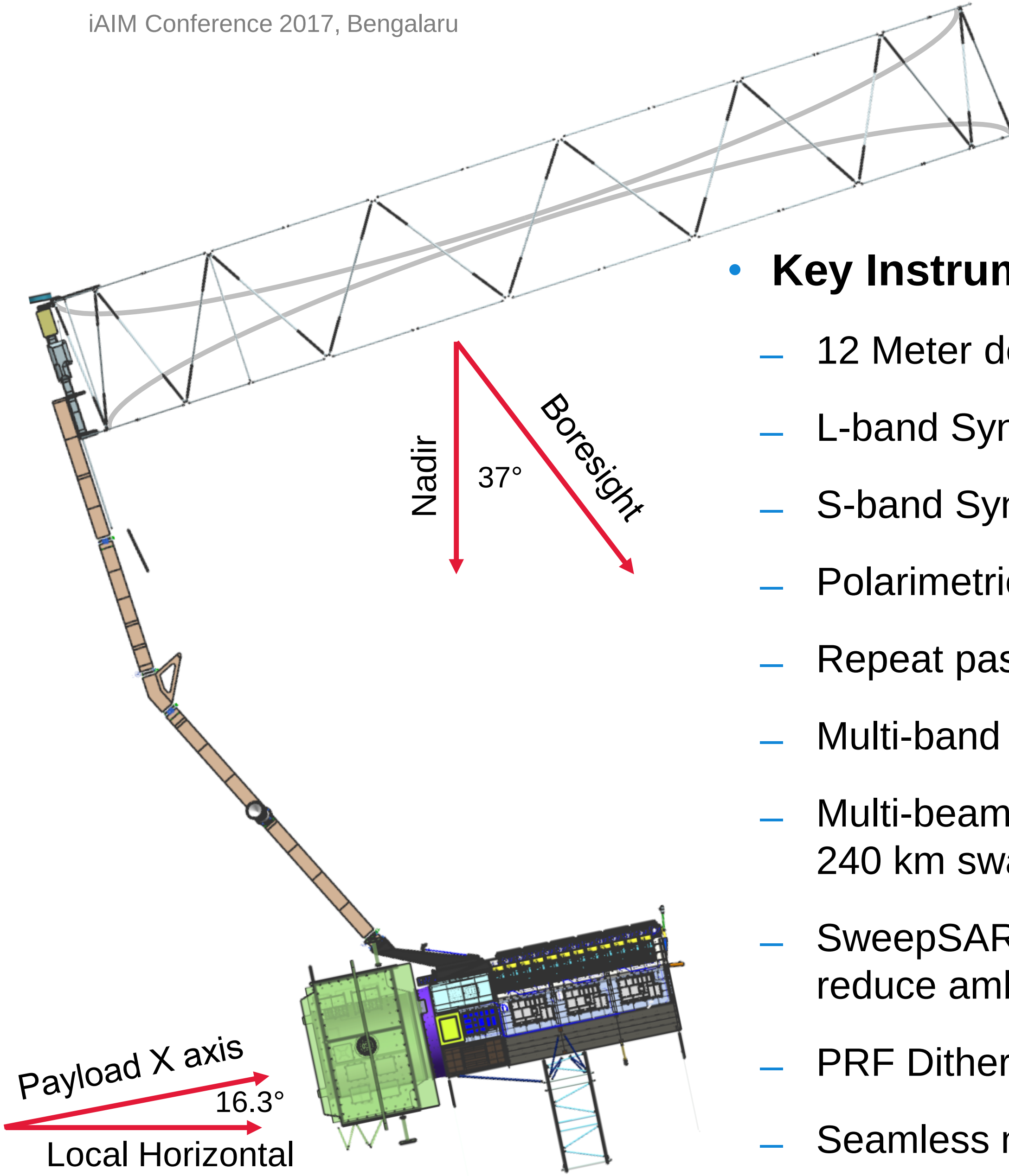
Rubber, banana, and oil palm trees,

Muar, Malaysia



Examples of dual-frequency measurements from SIR-C/X-SAR
ISRO L-/S-band Airborne Program will generate research products

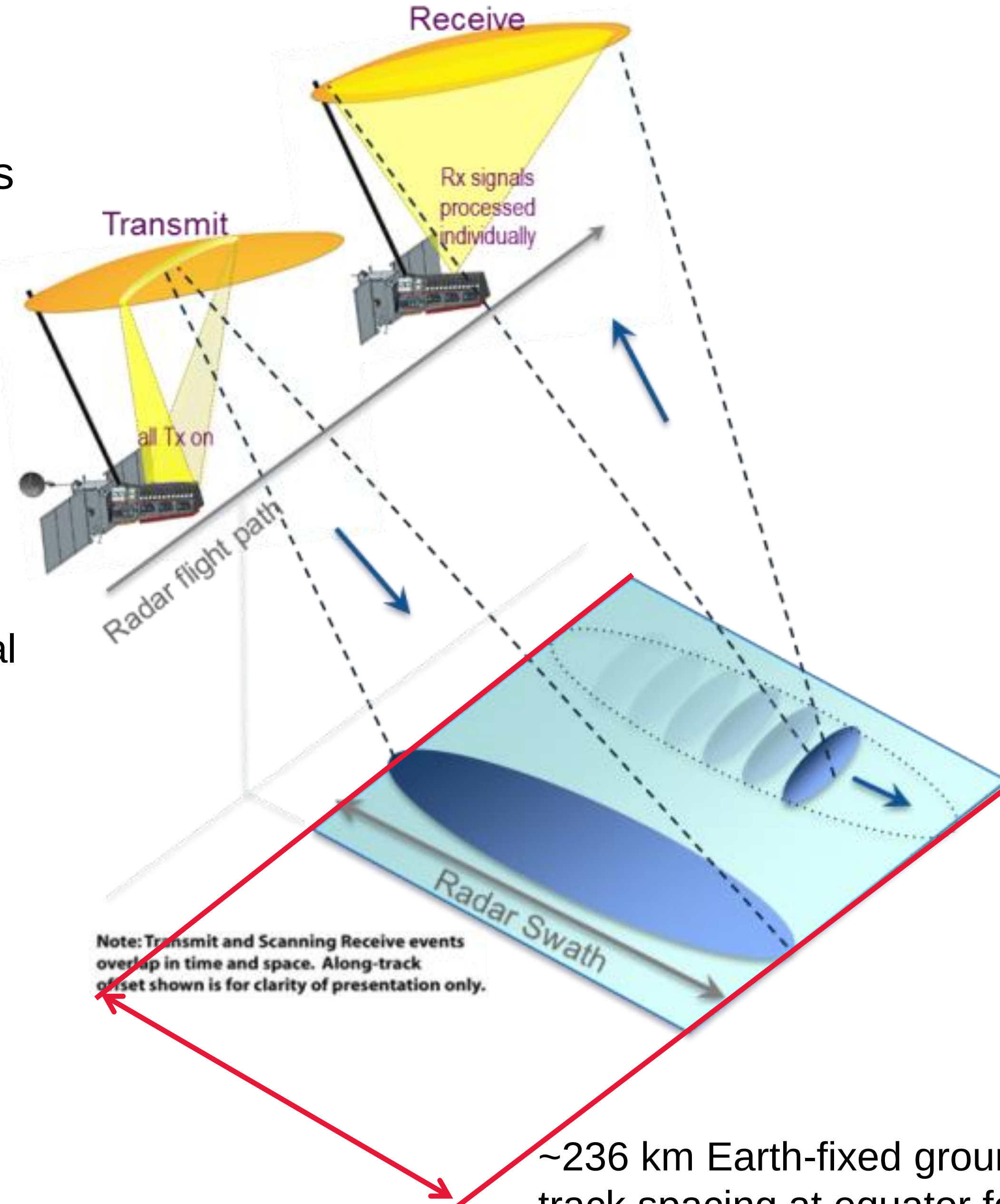
SAR Instruments



- **Key Instrument Features:**
  - 12 Meter deployable Mesh Reflector
  - L-band Synthetic Aperture Radar (1257.5 MHz)
  - S-band Synthetic Aperture Radar (2200 MHz)
  - Polarimetric for classification and Biomass
  - Repeat pass interferometer for deformation
  - Multi-band Spectrum for Ionosphere mitigation
  - Multi-beam Array fed Reflector to achieve a 240 km swath
  - SweepSAR timing and Digital Beam Forming to reduce ambiguities and preserve resolution / looks
  - PRF Dithering to fill transmit interference gaps
  - Seamless mode transitions to minimize data loss
  - On-board filtering and compression to reduce downlink

NISAR SweepSAR

- *SweepSAR* allows simultaneous
  - Wide swath
  - Fine resolution
  - polarimetry
- SweepSAR method:
  - Transmit pulse with full feed illumination
  - Track echo digitally with individual receivers (12 at L-band; 24 at S-band)
  - Assemble individually received signals into a full-swath measurement
- SweepSAR implemented independently by both JPL and ISRO
  - But radars are time-synced for dual-frequency operations

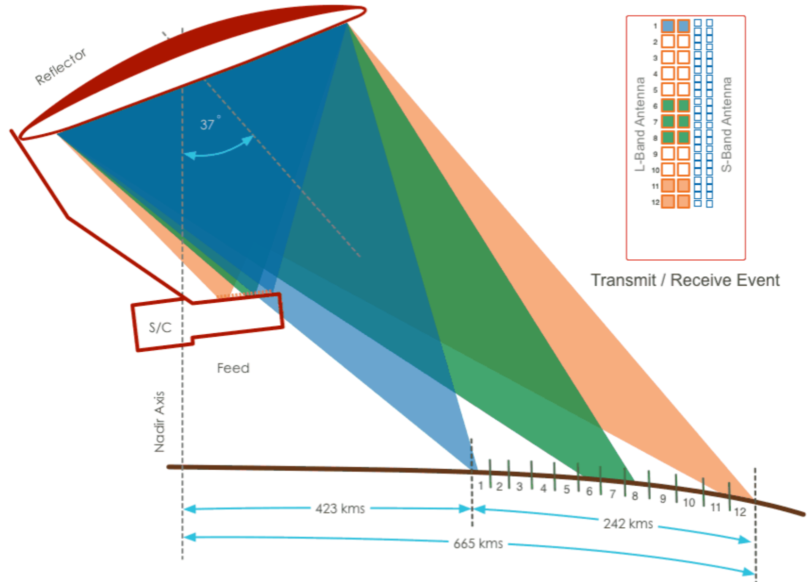


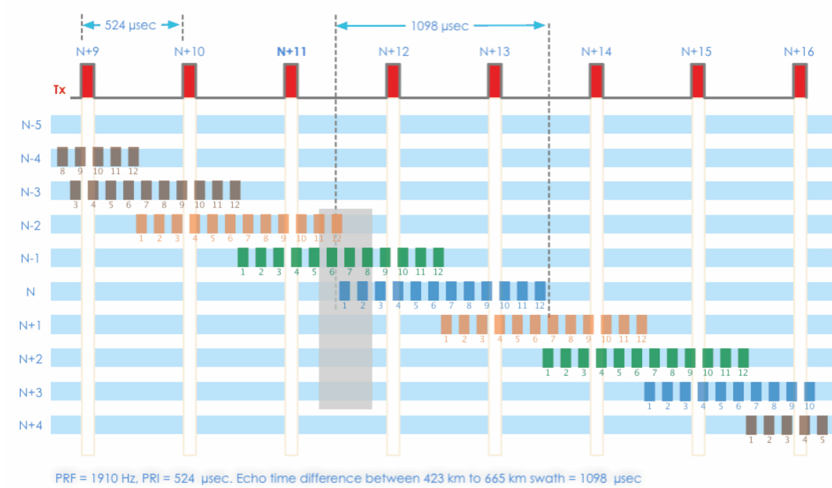
~236 km Earth-fixed ground track spacing at equator for 12-day repeat orbit

JPL

SweepSAR Measurement Technique

- **SweepSAR Basics**
  - On Transmit, illuminate the entire swath of interest (red beam)
  - On Receive, steer the beam in fast time to follow the angle of the echo coming back to maximize the SNR of the signal and reject range ambiguities
  - Allows echo to span more than 1 Inter Pulse Period (IPP)
- **Consequences**
  - 4 echoes can be simultaneously returning to the radar from 4 different angles in 4 different groups of antenna beams
  - Each echo needs to be sampled, filtered, Beam-formed, further filtered, and compressed
  - On-Board processing is not reversible – Requires on-board calibration before data is combined to achieve optimum performance

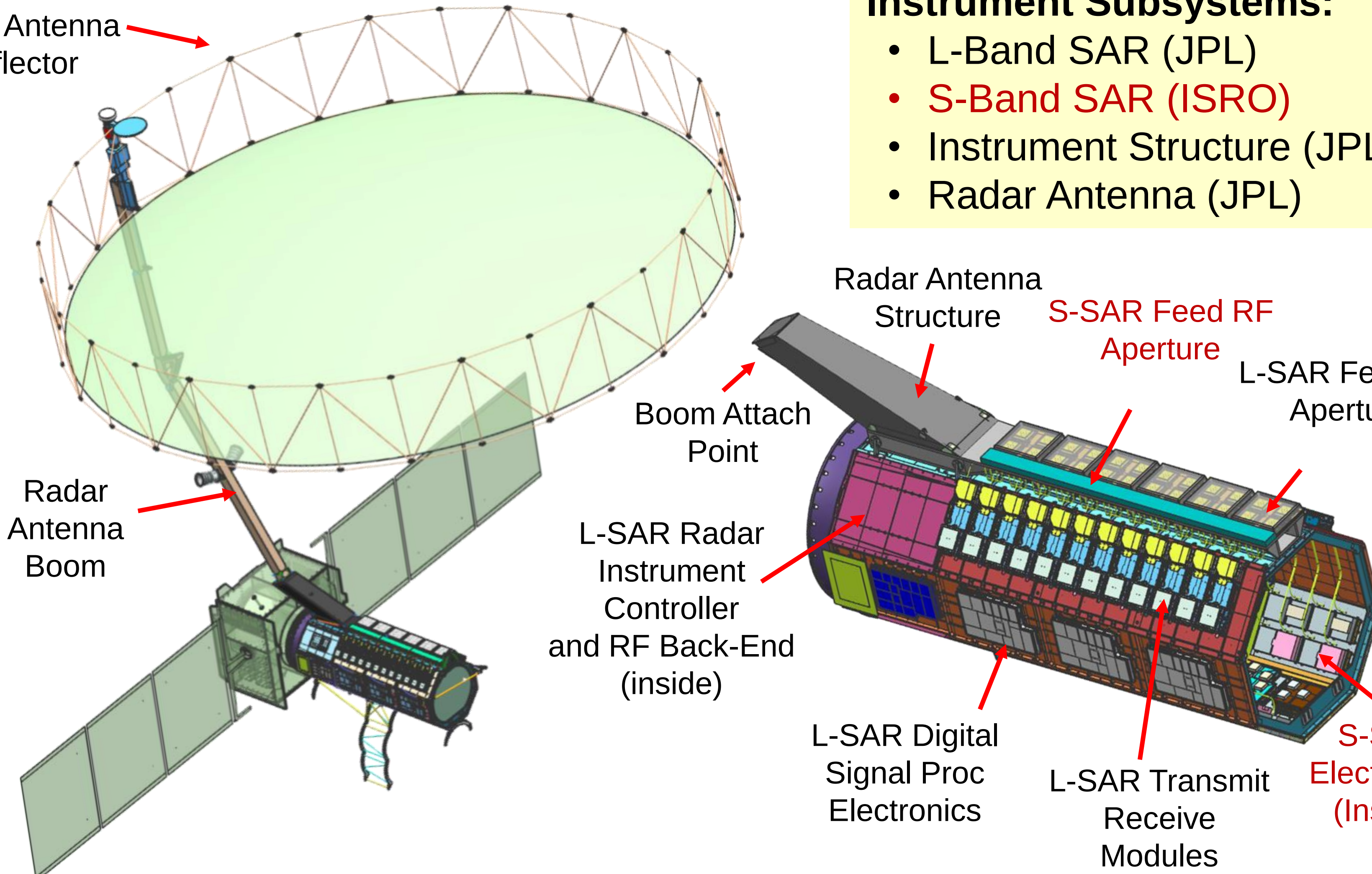




NISAR Instrument Overview

What is the antenna?

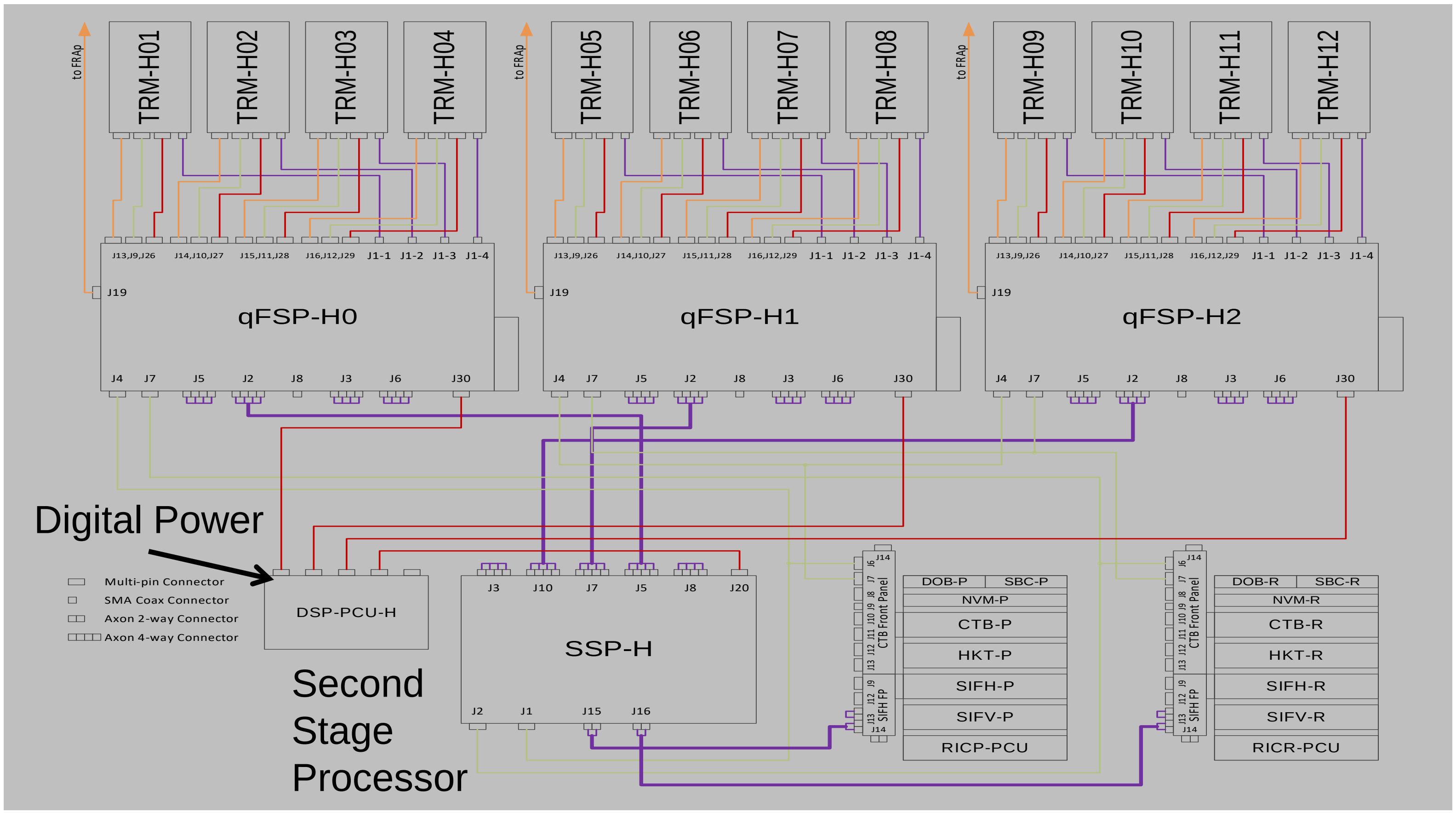
Instrument Subsystems:
- L-Band SAR (JPL)
- S-Band SAR (ISRO)
- Instrument Structure (JPL)
- Radar Antenna (JPL)



Instrument Structure also houses GPS unit and Solid State Recorder

L-SAR Electronics

(Only Horizontal Polarization Shown)



Transmit Receive Modules

First Stage Processors

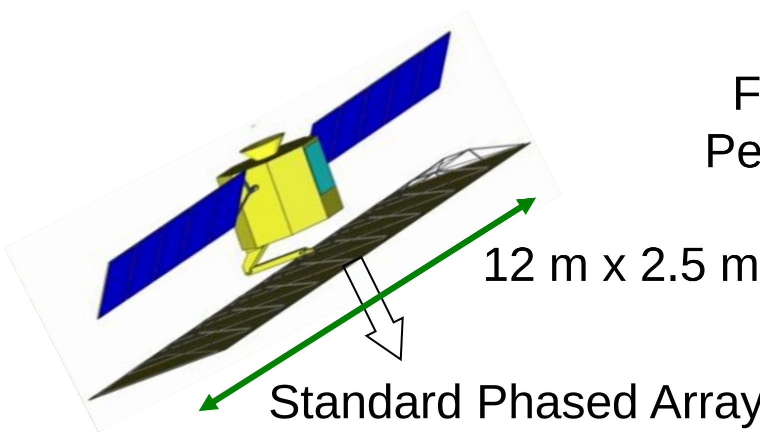
System Timing, Telemetry, Solid State Recorder Interface

Challenges in Developing the NISAR Antenna

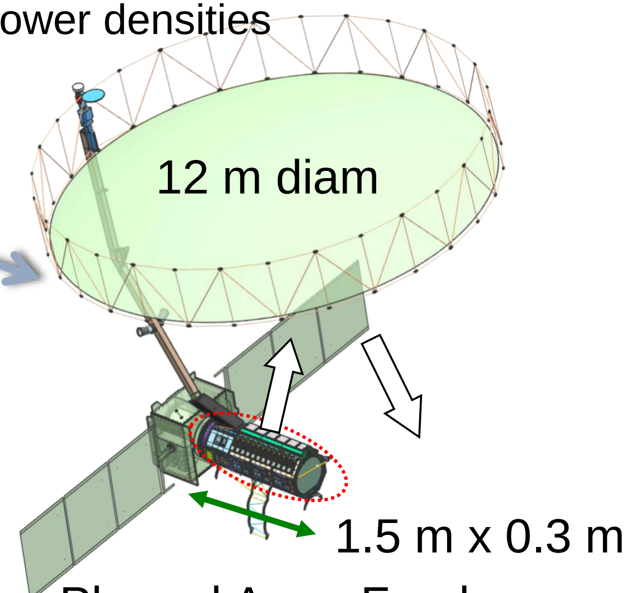
- Mechanical compact stowage and on-orbit stability
    - Reflector and Boom must stow inside launch vehicle fairing
    - Entire electro-mechanical structure must maintain or have predictable shape to millimeters over 5 years or more
- High power density of radar
- Feed performance over dynamic thermal environment
- Maintaining phase coherence of transmit and receive modules for modelable beam patterns and digital beam formation
- Verification of design by models (too big to deploy and measure)

High Power Density Phased Arrays

- The SweepSAR reflector architecture is expected to be more cost effective than a traditional phased array, but the RF and DC power densities become much higher
- Development focused on improving reliability for high power densities
  - Increase RF power density
  - Improve component stability
  - Enable new instrument architecture



For 2kW RF
Peak Radiated
Power



- Lower RF Power Density (67 W/m²)
- Larger Radiator Area (30 m²)
- Higher Thermal Inertia

- Higher RF Power Density (4000 W/m²)
- Smaller Radiator Area (0.5 m²)
- Lower Thermal Inertia

➔ GaN High Power Amplifiers: Increased RF output, decreased DC power and heat

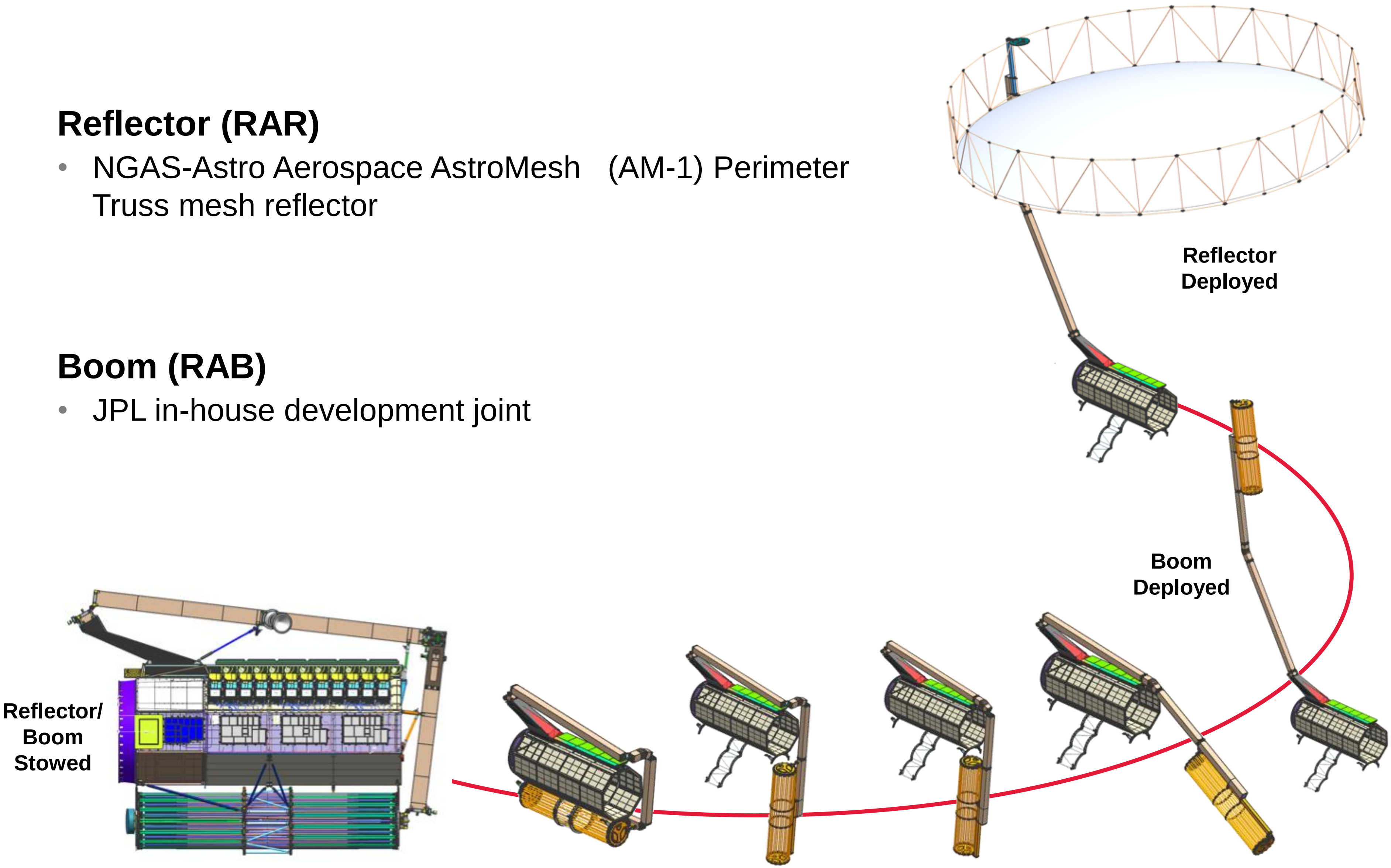
Reflector / Boom

Reflector (RAR)

- NGAS-Astro Aerospace AstroMesh (AM-1) Perimeter Truss mesh reflector

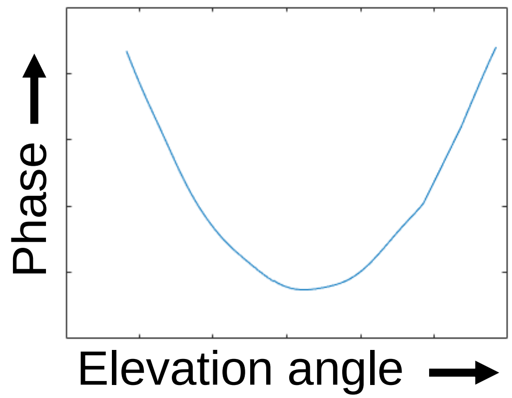
Boom (RAB)

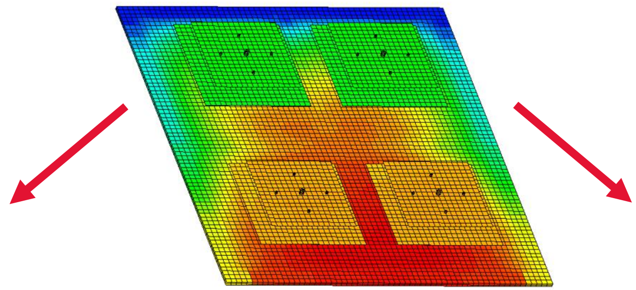
- JPL in-house development joint



Sources of Antenna Gain/Phase Change

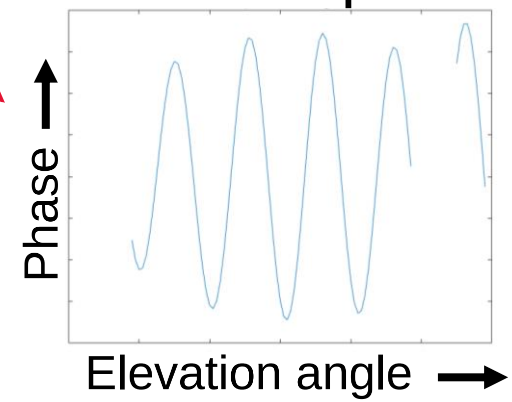
Feed deformation – mechanical path

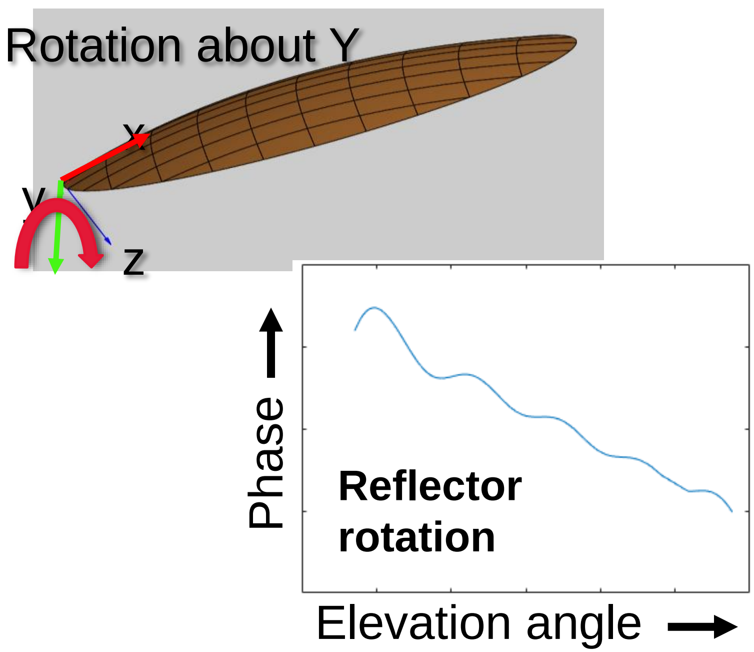


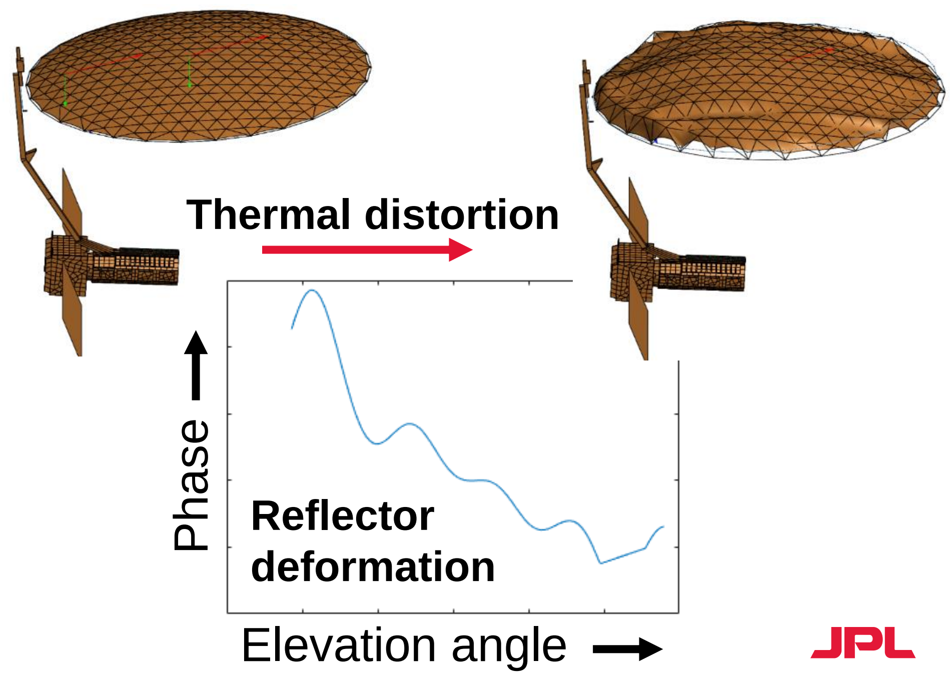


Thermal gradients on Feed Tiles/Structure

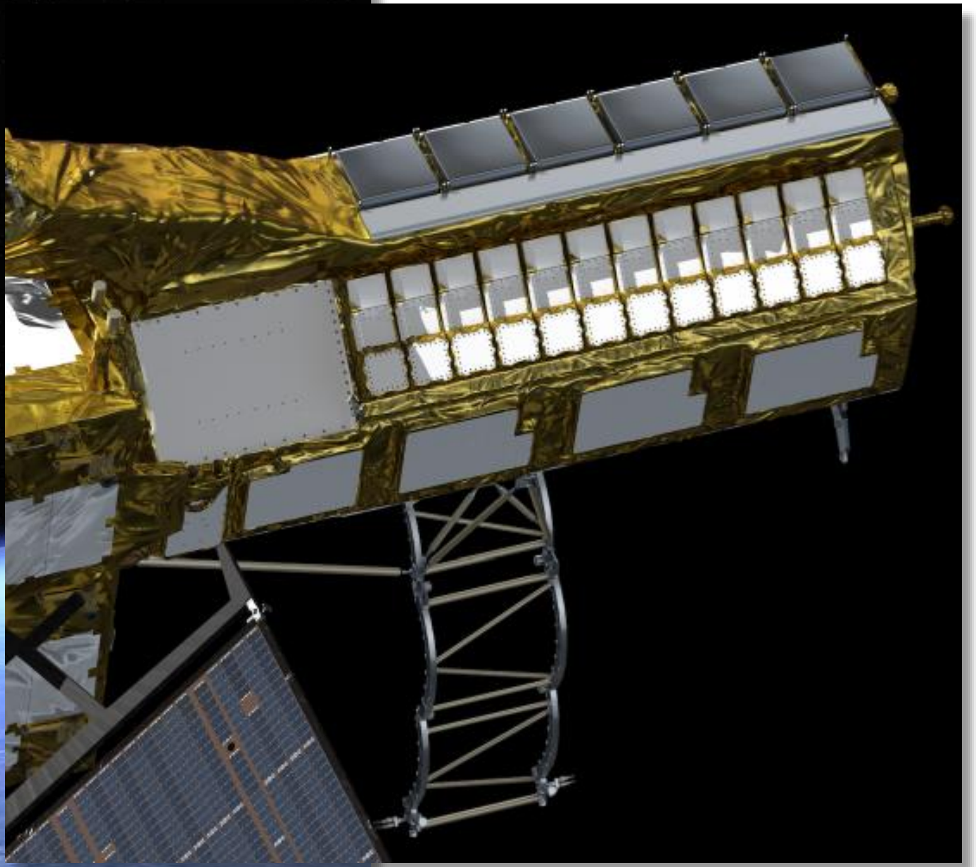
Tile electrical path







NISAR Observatory

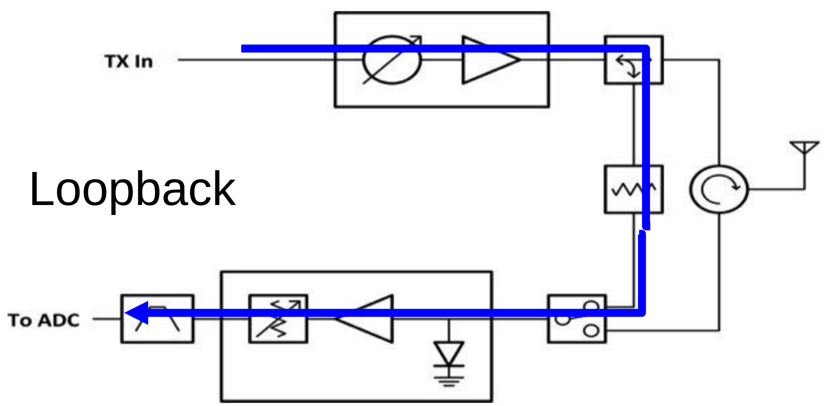


Real-time digital calibration

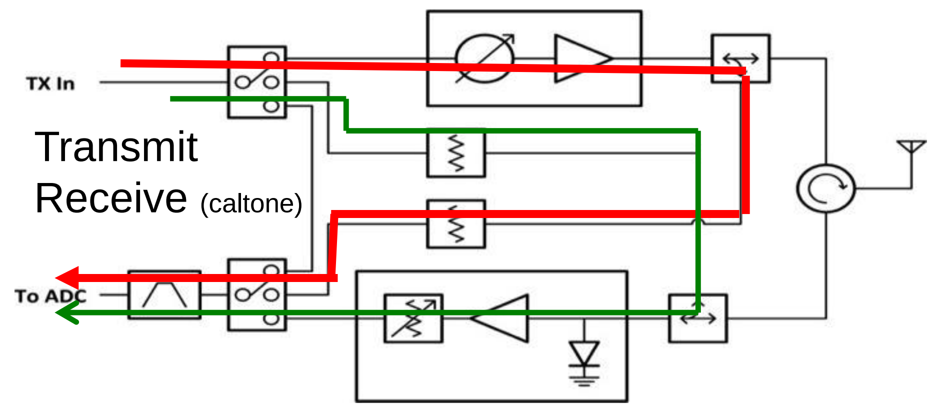
- The SweepSAR technique enables large swath imaging, but introduces new challenges
- 24 independent transmitters and receivers must be made to work as one, with little help from the ground
  - Data rates preclude sending all 24 channels to the ground for processing, so significant processing must take place on-board
  - Once channels are combined, errors in individual channels cannot fully be corrected, so this must take place on-board
  - Data volumes dictate that much of this processing must take place in real-time
- By leveraging the 24 independently digitized channels, we are able to calibrate both transmit and receive on-board, prior to beamforming

SweepSAR calibration concept

Traditional Loopback Calibration



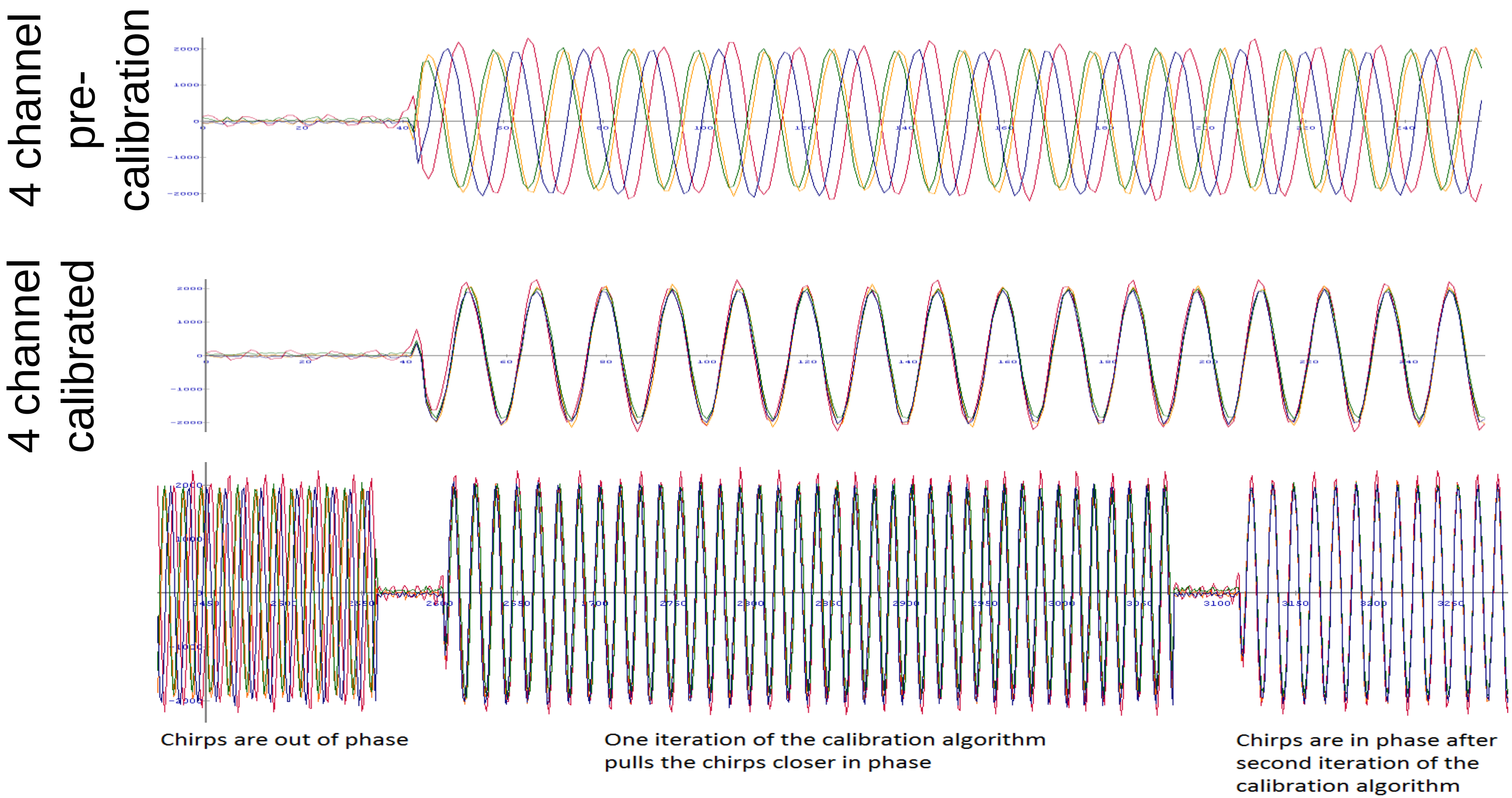
SweepSAR Digital Calibration



- **Relaxes the isolation requirement between TX and RX**
- **Calibration can be done during actual receive events**
- **Differentiates between TX and RX changes (important for SweepSAR)**
- **Compensates for all changes not just temperature**

Hoffman et al. (2015) “Digital Calibration System for the Proposed NISAR (NASA/ISRO) Mission”

Transmit Calibration Result Example



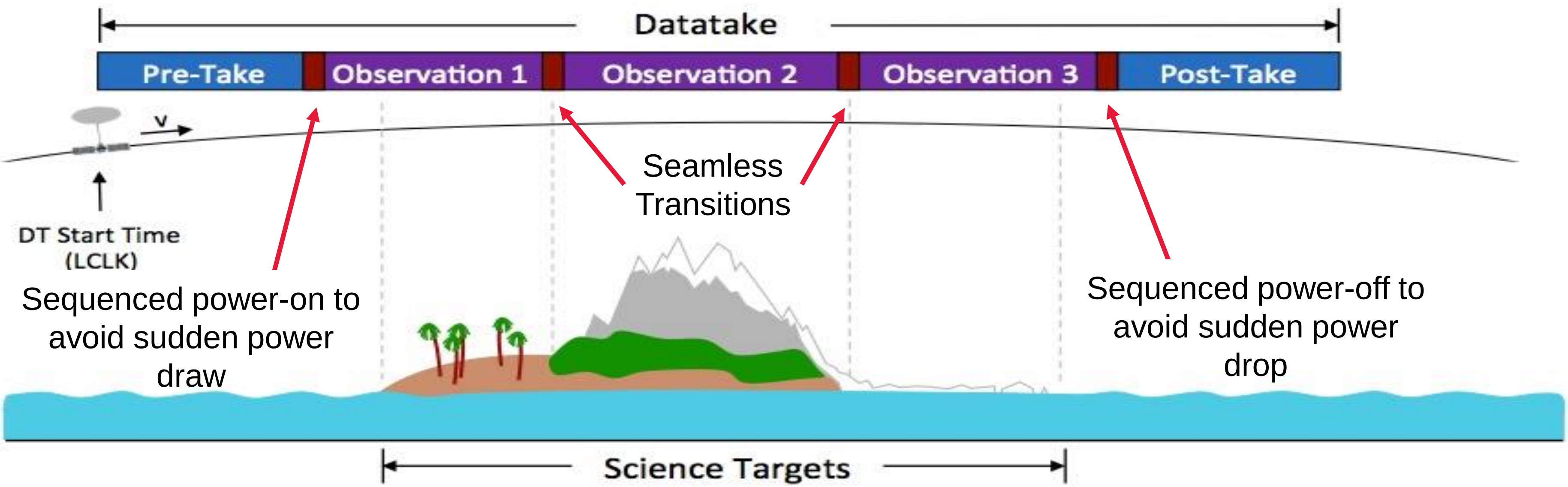
Calibration enabled here

Calibration iterates

Calibration Complete

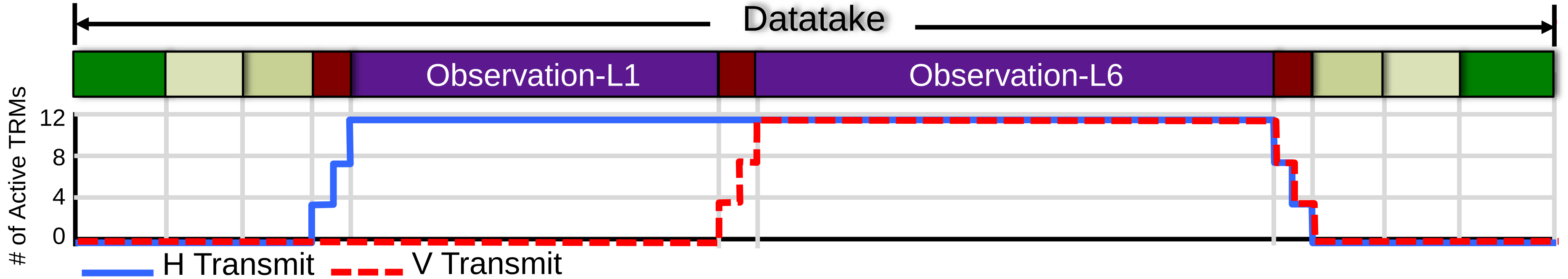
L- and S-band coordinated observations

- The L-band and S-band radars uses a set of upload-able tables to control radar operations
- Consecutive ***Observations*** with the same start time are grouped into a ***Datatake*** and collected back-to-back with seamless transitions between them
- Each Datatake has a Pre- and Post-take for calibration and at least one or



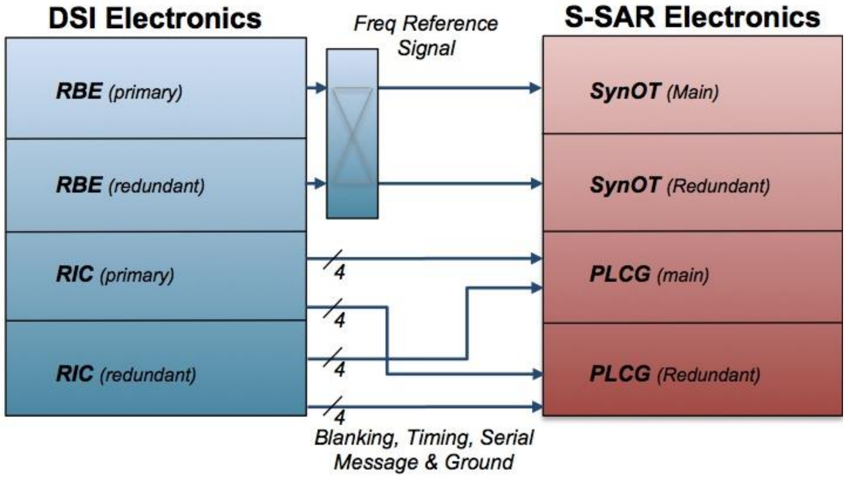
L- and S-band coordinated timing

- **Joint Data Take Timing Synchronization**
  - To avoid mutual interference during joint operations, transmit events are synchronized
  - L-SAR generates a Timing Reference Pulse and a Global Blanking Pulse and forwards them to the S-SAR electronics to ensure that the transmit events occur in sync
  - L-SAR transmits a digital message to the S-SAR to indicate pulse count, radar clock time, and other parameters to help align the operations of the two radars
  - S-SAR uses the L-SAR STALO and timing signals to derive its pulse timing signals
- **Datatake Power Sequencing**
  - Because of power system constraints, the transitions from idle to transmit and transmit to idle must be sequenced on to prevent transients on the bus
  - S-SAR also does power sequence, but offset from L-SAR to minimize transients on the power bus



L- to S-band electrical interfaces

- To ensure proper timing during joint radar operations, four signals are generated by the L-SAR radar electronics and provided to S-SAR. These signals consist of:
  - **Frequency Reference**: 10 MHz StaLO RF signal to derive timing signals (50ohm coax)
  - **Global Blanking Pulse**: Pulsed RS422 signal to synchronize transmit events
  - **Radar Timing Reference**: Pulsed RS422 to serve as a precise time marker
  - **Radar Serial Message**: Asynchronous serial message containing radar mode, L-SAR clock time, L-SAR pulse count, GPS time and position, etc.
- S-SAR uses L-SAR StaLO and timing signals to derive its pulse timing signals for any datatake that contains at least one joint observation



L-band SAR Hardware Progress to Date

EM Waveform Generator

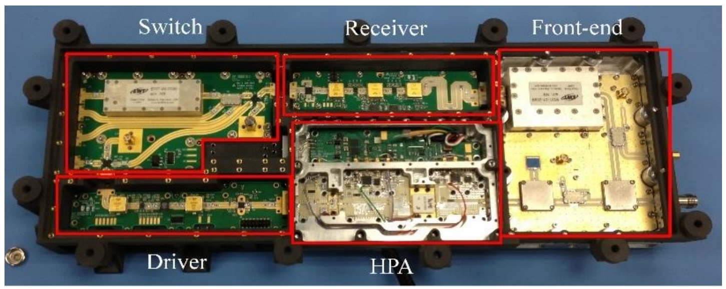
EM Up Converter Driver

EM Frequency Synthesizer

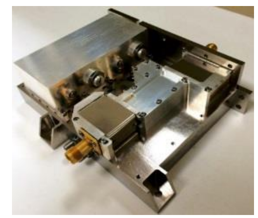
EM RBE-PCU

EM RBE Stack

EM TRM-ESS



TRM Pathfinder EM



EM Front-End Subassembly (FES)

Prototype and Pathfinder TRMs

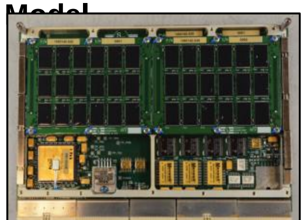
EM RIC-CTB

EM RIC-SIF

RIC- RAD750 Qual Model

EM RIC-HKT

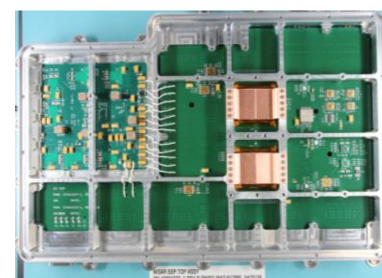
EM RIC-PCU



FM RIC-NVM (SEAKR)

Digital Signal Processor

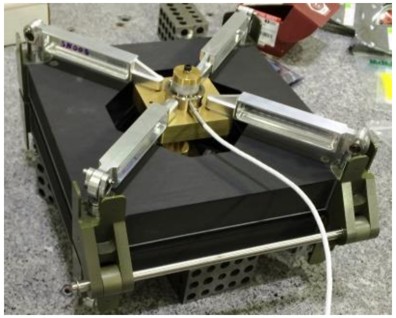
EM QFSP



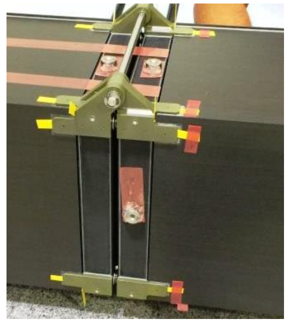
EM SSP

SAR Mechanical Hardware Progress to Date

Boom and Hinge Development Hardware



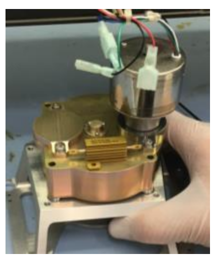
10" Development Boom Stability Test



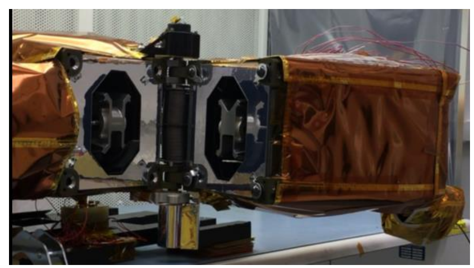
7" Prototype Boom/Hinge in fabrication

Hinge Deploy & Latching H/W

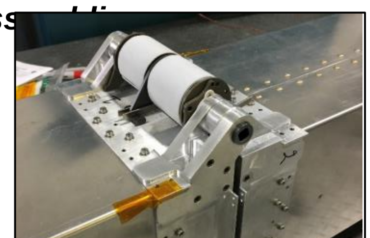
PT Spring Ass



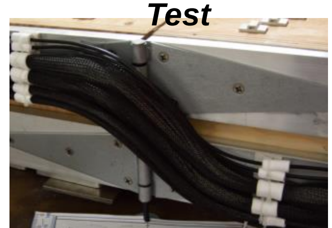
Boom Actuator PT



Prototype 7" Spring/Damper Deploy Test

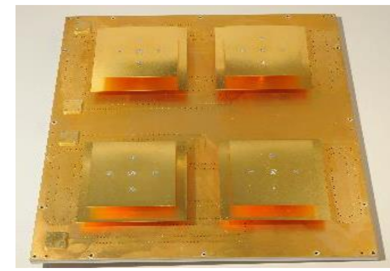


Hinge Spring Cartridge Torque Test



Boom Harness Torque Test

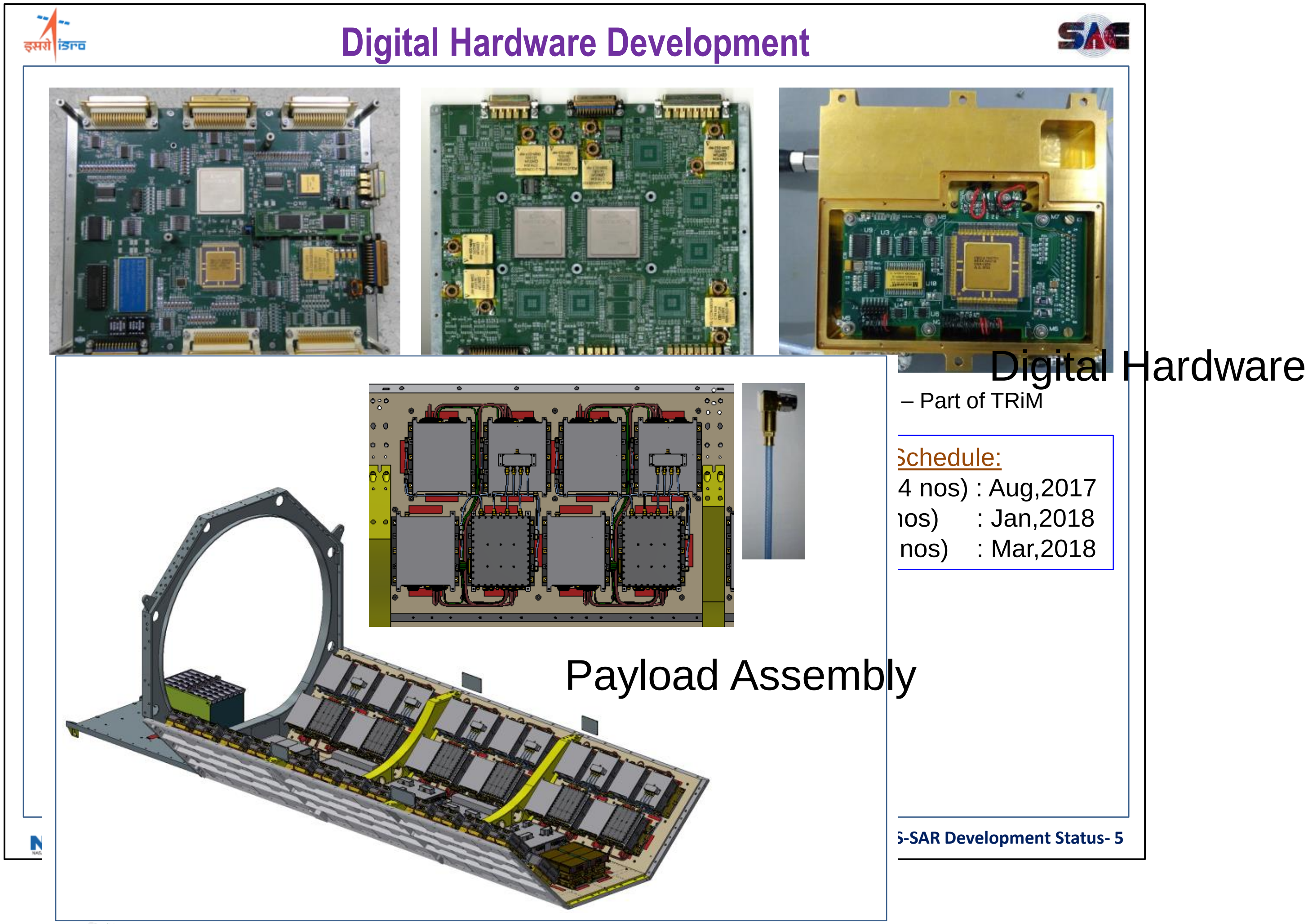
L-FRAP Feed Tile Development Hardware



Feed Tile EM (without radome)

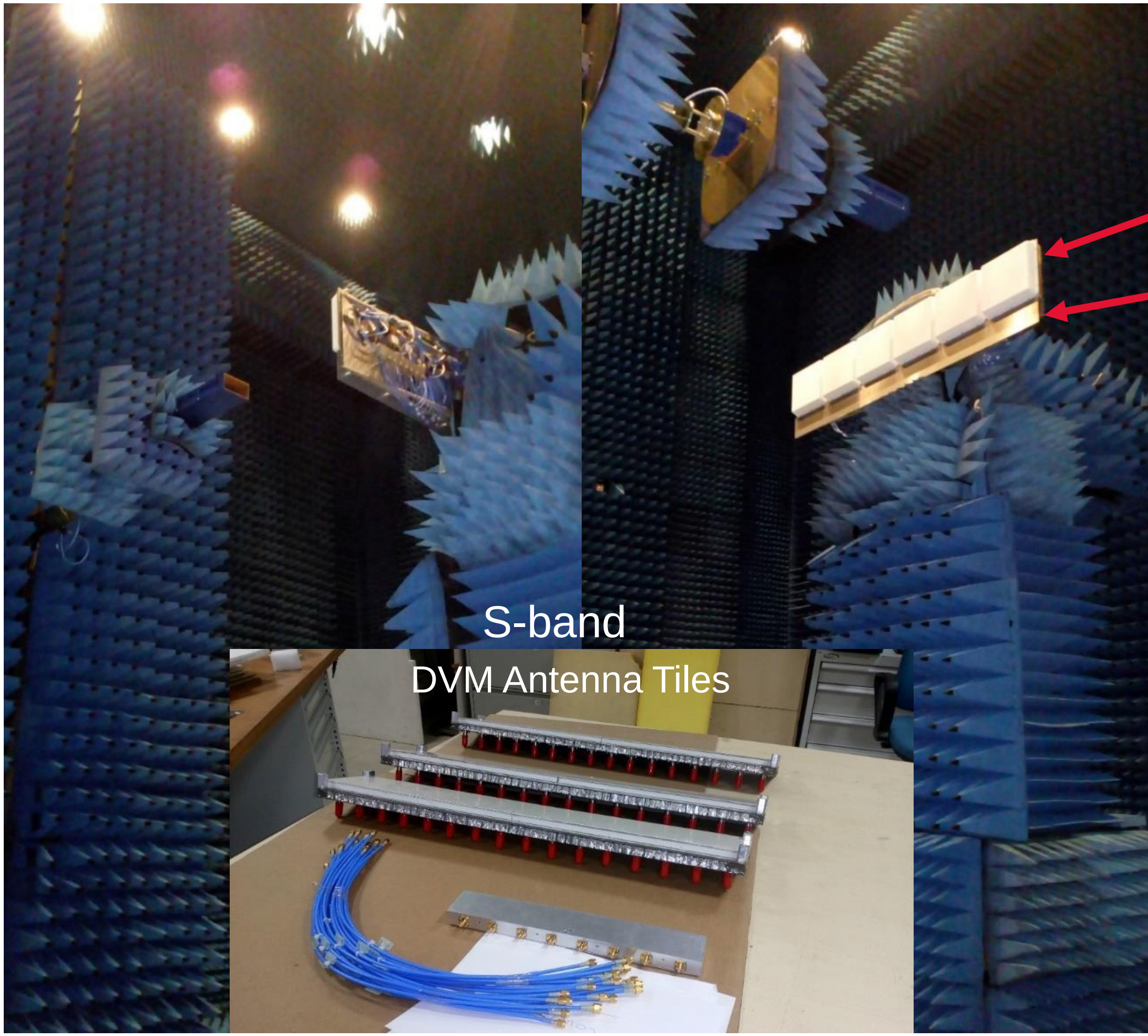
Feed Array EM in Test

ISRO S-band Hardware and Configuration



Front-end Radiating Aperture

S-band Development and Joint L+S compatibility



Testing of Joint Aperture at ISRO SAC

Summary

- The NISAR Mission will deliver first-of-a-kind science, enabled by dense time series over the globe at L-band and regionally at S-band
- The NISAR antenna system is a first-of-a-kind development designed to meet the demanding observation needs
- NISAR is a rewarding partnership between India and the US, each bringing unique perspectives to the scientific and technical developments

Jet Propulsion Laboratory
California Institute of Technology